Optical antenna: Towards a unity efficiency near-field optical probe

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(Received 22 October 1996; accepted for publication 13 January 1997)

We demonstrate that an antenna can be used to realize a near-field optical probe that combines spatial resolution well below the diffraction limit with transmission efficiency approaching unity. The probe consists of a planar bow-tie antenna with an open-circuited gap at its apex. We present proof-of-principle measurements using microwave radiation and discuss scaling the antenna to the visible optical spectrum. © *1997 American Institute of Physics.* [S0003-6951(97)03311-1]

Near-field optics, which enables optical imaging with spatial resolution significantly better than the diffraction limit, has recently found application in many diverse fields.[1] The invention of the tapered fiber probe,[2] with its much improved transmission efficiency, has enabled this recent period of growth. However, the efficiency of the tapered fiber probe is still orders of magnitude smaller than unity. For example,[3] a probe of diameter $\lambda/10$ has a transmission efficiency of order 10^{-5}. This low efficiency limits use of the tapered fiber probe to applications with either large photon fluxes or slow acquisition rates. A probe with unity efficiency would make near-field optics more generally applicable. Realizing such a probe remains one of the major challenges for near-field optics.

It is a well known principle of microwave engineering that the most efficient way to couple far-field radiation to a device of dimension much smaller than the photon wavelength is to attach the device across the terminals of an antenna.[4] When the antenna is properly impedance matched to the device, all of the incident power will couple to the device. Applying this to near-field optics, the antenna should couple far-field optics to a radiating device. This has previously been suggested by Fee *et al.*,[5] who proposed coupling an antenna to a coaxial cable and using the coaxial cable as a near-field probe. We propose a much simpler scheme and demonstrate that it works.

The antenna we have chosen is the bow-tie antenna, which is well known to be an efficient planar antenna.[6] The radiating device is simply the open circuited terminals of the antenna. As shown in the inset to Fig. 1, the terminals are truncated such that the antenna has a gap of width $d \ll \lambda$. When illuminated with electromagnetic radiation, currents induced in the arms of the antenna are guided towards the terminals. Because the terminals are open circuited, charge accumulates at the terminals resulting in displacement current across the gap. This displacement current radiates like a Hertzian dipole[7] of length d.

To test this idea, we built a scale model system at 2.20 GHz ($\lambda = 13.6$ cm). The system is shown schematically in Fig. 1. The bow-tie antenna is made of aluminum and has an opening angle of 90°. The total length, L, of the antenna is 36 cm (2.6λ), the thickness is 1 cm, and the terminals of the antenna form a cubic gap of width d equal to 1 cm ($\sim\lambda/14$). The antenna is illuminated by placing it 2.5 cm in front of the open end of a full height rectangular waveguide. Images of the local electromagnetic energy density are generated by scanning a dipole probe in a plane perpendicular to the waveguide axis (i.e., in the $\mathbf{E}-\mathbf{H}$ plane indicated in Fig. 1). The arms of the dipole probe are of total length 0.7 cm ($\sim\lambda/20$) and the probe has an integrated coaxial balun.[8] For reference, images were also made of the radiation emitted by the waveguide without the antenna in the system. Shown in Fig. 2(a) is an image taken in a plane 2.5 cm in front of the open end of the waveguide (i.e., the eventual position of the antenna) without the antenna in the system. This profile is roughly Gaussian with a diameter of order 7 cm ($\sim\lambda/2$), as shown in Fig. 3. This demonstrates that the radiation emitted from the waveguide approximates that of a focused "optical" beam.

Figure 2(b) is an image of the energy radiated by the antenna. The image plane is 0.5 cm ($\sim\lambda/30$) in front of the antenna. The energy density is strongly localized in the gap region of the antenna and confined on the length scale $\lambda/10$. This is quantified in Fig. 3, where the data points shown as squares represent a scan in the direction of electric field polarization and the data points shown as circles represent a scan in the direction of magnetic field polarization. (The polarization directions are indicated in Fig. 1.) These data clearly show that all the light on the front side of the

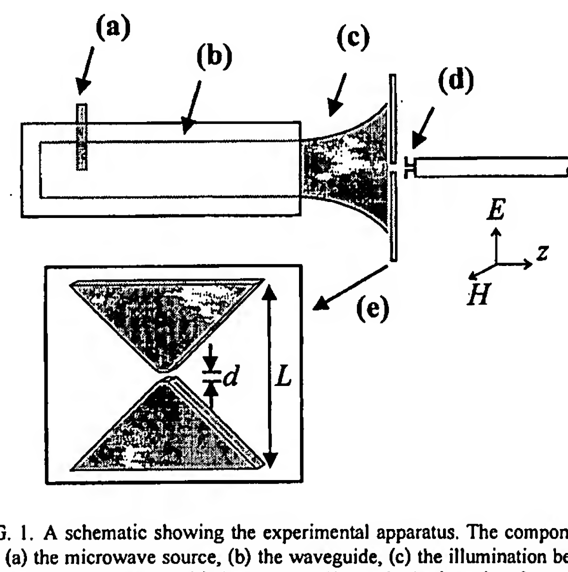

FIG. 1. A schematic showing the experimental apparatus. The components are (a) the microwave source, (b) the waveguide, (c) the illumination beam, (d) the dipole probe, and (e) the antenna. Shown in the inset is a front view of the antenna. Important dimensions are the total length, L, and the size of the gap, d. The incident electric field, $\mathbf{E}$, is oriented in the direction of the gap while the incident magnetic field, $\mathbf{H}$, is oriented perpendicular to the gap.

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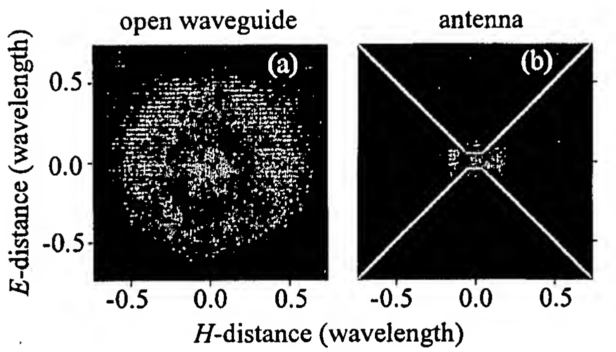

FIG. 2. Image (a) is the field intensity 2.5 cm in front of the open end of the rectangular waveguide. Image (b) is the field intensity measured 0.5 cm in front of the bow-tie antenna, which is positioned 2.5 cm in front of the open end of the waveguide. The axes of the images are the incident electric field, **E**, and magnetic field, **H**, directions and are normalized to photon wavelength. The image of the antenna is overlayed in (b) as an aid to the reader.

antenna originates from the gap. This image proves that *one does not need to force light through an aperture to produce a highly localized source of photons.*

The unique aspect of this new near-field "optical" probe is that it exhibits very large transmission efficiency. We measure transmission efficiency by measuring the power radiated by the antenna along the z-axis (i.e., axial with the waveguide, perpendicular to the $\mathbf{E}-\mathbf{H}$ plane) and comparing that to the power radiated by the open ended waveguide. The dipole probe used as the detector for these measurements has a total length equal to 3.4 cm ($\sim\lambda/4$). Because both curves fall off as an inverse square law in the far-field, their ratio in the far-field yields a rough measure of the transmission efficiency. Shown in Fig. 4 is a plot for the open waveguide (squares) and for the bow-tie antenna placed 1.3 cm in front of the waveguide (triangles). The ratio of these two curves in

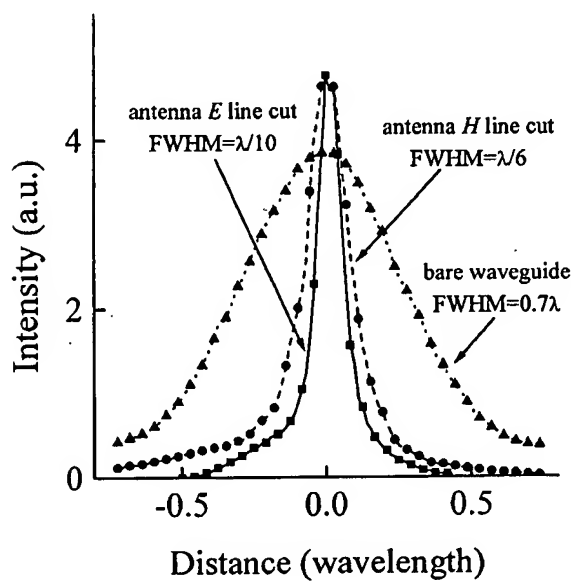

FIG. 3. Line cuts through the images in Fig. 2. The bare waveguide (triangles) shows a full width half-maximum (FWHM)=0.7λ. The E-direction line cut (squares) and the H-direction line cut (circles) through the antenna image, Fig. 2(b), have a FWHM of $\lambda/10$ and $\lambda/6$, respectively, clearly demonstrating that the antenna is acting as a near-field optical source.

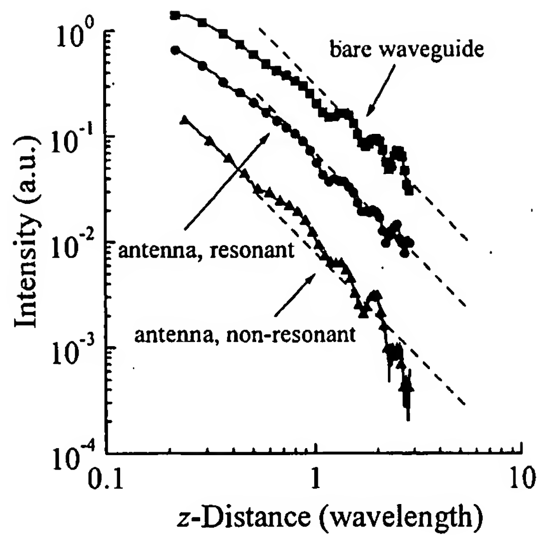

FIG. 4. Plots of the radiated power along the z-direction (i.e., axial) for the bare waveguide (squares), the antenna positioned resonantly with respect to the open end of the waveguide (circles), and the antenna positioned nonresonantly (triangles). The dashed lines are drawn as an aid to the reader and indicate inverse square law power dependence. The ratio of the nonresonant data to the bare waveguide data yields a transmission efficiency of order two percent, while the ratio of the resonant data to the bare waveguide data yields a transmission efficiency of order 30%.

the far-field yields an efficiency for the antenna of order 2%.

We model the efficiency of our optical system with an electrical circuit.[9] Consider free space as a 377 Ω transmission line. The antenna functions as a transformer. In particular, our self complementary bow-tie antenna transforms 377 Ω to 188 Ω. The antenna is terminated in a device, which in this case is the gap. The gap behaves like a capacitor, $|Z_c| = 1/(\omega\varepsilon_0 d) = 60\,(\lambda/d)\ \Omega$, in series with the radiative resistance of a Hertzian dipole, $Z_r = 80\pi^2(d/\lambda)^2$. The radiative efficiency of this circuit is

$$\frac{4Z_r 60\pi}{|Z_c|^2+(Z_r+60\pi)^2} \approx \frac{4Z_r 60\pi}{|Z_c|^2} = \frac{16\pi^3}{3}\left(\frac{d}{\lambda}\right)^4 \approx 0.5\%$$

for $\lambda/d \approx 14$. This agrees with our experimental observation to within a factor of 4 and explains the unusually large transmission efficiency of this probe.

We are also able to configure the system so as to yield even larger transmission efficiencies, of order unity. Shown in Fig. 4 is a plot (circles) for an antenna placed 6.8 cm ($\sim\lambda/2$) in front of the open end of the waveguide. This configuration results in a resonant cavity formed between the antenna and the end of the waveguide flange. The transmission efficiency for this configuration is of order 30%! We attribute this near unity efficiency to the cavity which acts to recycle photons that are reflected by the antenna. Within the context of our circuit model, the cavity is analogous to putting an inductor in parallel with the gap, making a tank circuit. We tested the tank circuit model experimentally by placing an inductive shunt across the gap and found that this also resulted in transmission efficiencies of order unity.

The near-field probe described above is essentially an electric dipole coupled to free space via an antenna. Traditional near-field optical probes, such as the tapered fiber

probe, are effectively magnetic dipoles coupled to free space via a metal plane.[10] Both the antenna and the electric dipole aspects of our new probe constitute significant conceptual advances over the traditional probe for two reasons. First, the near-field of a radiative electric dipole is dominated by electric fields while the near-field of a radiative magnetic dipole is dominated by magnetic fields. Because the magnetic interaction with matter is negligible at visible frequencies, one would rather have a probe based on an electric dipole than a magnetic dipole. Second, the coupling efficiency to any device is improved by using an appropriate antenna.

Antenna based probes like those of Fig. 1 can be easily fabricated for use at visible wavelengths using high resolution lithographic techniques. They could be incorporated into scanned probe microscopes via many techniques. For instance, they could be fabricated on the bottom of a solid immersion lens for scanning relatively flat samples. For samples with topography, it may be possible to make an antenna by appropriately metalizing the pyramidal walls of a conventional atomic force microscope probe. Regardless of the specific geometry, an open question remains as to whether antennae are efficient enough in the visible spectrum to be useful. We believe that the answer has to do with the ability of the incident photon to generate electric current in the metal arms of the antenna and thus drive charge to the antenna terminals. For real metals the surface current is approximately that of a perfect metal as long as the magnitude of the index of refraction is large in comparison to unity. This condition exists throughout much of the visible spectrum for metals such as gold and aluminum.[11]

In conclusion, we have shown that at microwave frequencies a planar bow-tie antenna with open circuited terminals functions as a near-field optical probe with transmission efficiency of order unity. We provide a theoretical understanding of this result within the context of a simple circuit model. The antenna coupled electric dipole represents a new paradigm for near-field optical probes and may provide a foundation on which to make near-field optics more widely accessible to the scientific community.

The authors acknowledge useful discussions with R.G. Wheeler, R.K. Chang, P.J. Kindlmann, and D.W. van der Weide. This work was supported in part by the U.S. Army Research Office under Grant No. DAAH04-95-1-0368.

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